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QUARTERLY PROGRESS REPORT NO. 1

Solid State Thermostat

Contract NAS 8-11625

Prepared for:

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Quarterly Report No. 1 Contract NAS 8-11625

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ADDENDA

18 August 1964

QUARTERLY REPORT NO. 1
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1. INTRODUCTION

This report covers the progress made and the results obtained during the first three months of the duration of this contract. The end of the reporting period coincides with the conclusion of the first important phase: development of a suitable circuit.

While electronic problems mainly have been solved, certain packaging problems still remain. In the following, the adopted design approach is discussed and the test results obtained from the breadboard given.

2. PROGRESS DURING THE REPORTING PERIOD

During the reporting period, studies of sensing methods were carried out and led to the adoption of a scheme where the thermistor sensing element is placed in the feedback path of a DC amplifier. The circuit necessary to implement this sensing method was developed and tested. The attached schematic diagram shows the final circuit, and the parts list describes the components intended for use in the final product.

The difficulty in trying to meet the requirement for a dual output function (temperature readout and switching) dictated a more complicated electronic circuit than originally anticipated. Attempts to solve this difficulty by employing integrated amplifiers of the type micro-A 702 produced by Fairchild failed. Therefore, it must be said that the size requirement of the specifications cannot be met. A preliminary layout using Cordwood packaging techniques indicated that the final size would be 1-1/4" diameter x 2" length.

These packaging difficulties led to a delay with respect to the program plan. However, this delay is insignificant, and will not influence delivery date. The packaging of the electronic circuit has been started.

3. THE DESIGN APPROACH

3.1 The Problems

The function of the thermostat to be developed under this program is twofold. It has to provide a temperature readout signal and a solid state switch capable of handling one ampere of current.

It is intended to sense the temperature of various media, as gases, liquid and solids. Accuracy and fast response are important requirements. The response time of the entire thermostat is influenced mainly by the large time constant of the sensing element. Therefore, it demands a very small thermistor. Small thermistors, however, show significant self-heating, an effect which especially in a gaseous medium might lead to significant error. In order to combat this error and still maintain fast response, the thermal mass of the sensing element must be kept as small as feasible. Unfortunately sensing elements with small time constants feature large dissipation constants - that is to say, show significant self-heating effect. Therefore, the power dissipation of the sensing element must be kept low. This leads to a compromise between the impedance of the thermistor and the voltage across it.

The sensitivity of the sensing circuit depends mainly on the voltage across the thermistor. Therefore, this voltage should be as high as feasible.

A high voltage can be applied to the thermistor when its impedance is high, thereby keeping the power dissipation low. Unfortunately, this creates the second problem. A high impedance circuit cannot be loaded without introducing intolerable errors. We need a buffer amplifier. The output of such a buffer amplifier would be a function of the temperature and can be used as readout. However, for the switching action we need far better resolution and, consequently, higher gain. This leads to the requirement of a second amplifier.

In the switching section of the thermostat, a large current with respect to the size of the thermostat has to be handled. Here we face the problem of keeping the power dissipated in the circuit to a minimum and of conducting this heat to the environment.

Data handling imposes another requirement. It is desirable to have one universal calibration curve for all units. This leads to stringent specifications as to the tolerance of the sensing element.

3.2 The Solution

The circuit shown in the attached schematic diagram solves the above problems. It consists of a power supply, a sensing circuit, a buffer amplifier, a zero amplifier and a high current switch. The temperature sensor is placed in the feedback path of the buffer amplifier. The result is an operational amplifier whose gain varies, depending on the sensor temperature.

This method of sensing leads to the desired temperature-voltage characteristic at the output of the amplifier, and avoids excessive loading of the thermistor. The output of the amplifier provides the readout signal. The output of the buffer amplifier is compared to the constant voltage established by the Zener reference diode CR_4. The ratio of R16 to R17 is chosen in such a manner that at the desired switching temperature, the input voltage at the base of Q9 is approximately zero. A temperature change will cause this voltage to deviate from zero. This deviation is amplified by the zero amplifier, and then used to operate the switch.

While the buffer amplifier has a variable gain depending on the temperature, the zero amplifier has a fixed gain of about one hundred to assure sufficient sensitivity. Positive feedback through R22 from the power switch to the non-inverting input of the amplifier reduces switching transients and protects Q15 from "partial turn-on". Without positive feedback it can happen that only half the load current (.5A) is flowing into the load. Then one half of the supply voltage appears across the load and the other half across Q15 (partial turn-on). This would cause exesss- ive power dissipation in Q15, leading to its destruction.

The positive feedback is activated only when Q14 starts to conduct, which occurs when the switch point temperature is reached. It causes some "on-off" differential (hysteresis) which can be influenced by the magnitude of R27. R27 is selected for an "on-off" differential (hysteresis) of about .1°C at 25°C.

The switching portion of the thermostat consists of the power transistor Q15, the driver transistor Q14, and the amplifier stage Q13. Here the main design objective was to keep the power dissipation of Q15 low. This is accomplished by inserting CR7.

This power reduction can be explained when we assume that the base of Q15 is connected to the 28 volt supply. Now both base and collector are connected to the same voltage. By tying base and collector together, both voltages with respect to the emitter must be the same. Therefore, the large base-emitter voltage would appear across the collector-emitter junction and power dissipation would be high. This is aggravated by the fact that the base is connected to the 28 volt line through Q14. The collector-emitter voltage of this transistor would be added to the base-emitter voltage of Q15. If no diode is inserted between the 28 V line and the collector of Q15, a voltage in the order of 1.5 volts would appear across collector-emitter junction, leading to a very large power dissipation. The diode CR7 cuts this voltage, thereby cutting the power in half.

The power supply provides two regulated voltages, +20 V and -6V. The reference voltage for temperature readout and the switch point is derived from the -6V supply. An inverter circuit produces the negative supply voltage. The inverter is also used to supply a constant voltage to the amplifier stage Q2 of the voltage regulator, making it possible to obtain excellent regulation against line voltage changes.

The packaging problem could not be solved entirely satisfactorily. The large number of components did not permit packaging to the specifications.

An attempt was made to reduce the number of components of the circuit by employing integrated DC amplifiers of the type μ A702 produced by Fairchild. Such an amplifier would occupy only the space of one transistor. Unfortunately, this substitution failed because of the low input impedance of the μ A702 amplifier.

The highest density obtainable by Cordwood packaging will lead to a case size of 1-1/4 inch diameter x 2 inches length.

3.2.1 The Sensor

A good temperature sensing element should have the following characteristics: 1. stability in time; 2. high sensitivity; and 3. a reproduceable characteristic. Fenwal Electronics offers such a device, the IsoCurve thermistor. Its disadvantage - non-linearity - is outweighed by the fact that this thermistor is available matched to a standard curve. This allows the use of one calibration curve for all units.

From the beginning it was clear that a simple thermistor network cannot accept loads which vary in the order of 3% and still meet the specifications. The impedance level of a thermistor network would have to be low, while the excitation voltage would have to be high to obtain the required sensitivity. Both low impedance and high excitation voltage lead to a high power dissipation in the thermistor. Appreciable self-heating would occur and a significant error be introduced. A buffer amplifier solves this problem.

The specifications call for an accuracy of ±.2°C in a different temperature interval, viz., 25°C to 50°C, is required.

The switch point accuracy requires a better stability than that which would be sufficient for the readout. This stability is mainly decided by the buffer amplifier. An amplifier would display essentially the same stability over its useful output voltage range. The stability requirement, therefore, would be decided by the switch point stability.

A circuit which relieves this rather stringent stability requirement could take advantage of the nonlinearity of the thermistor sensor. If a circuit can be found where the sensitivity in the switching range (25°C to 50°C) is higher than in the remaining readout range (0°C to 25°C), the stability requirement for the amplifier can be eased. Figure 1 shows the adopted solution.

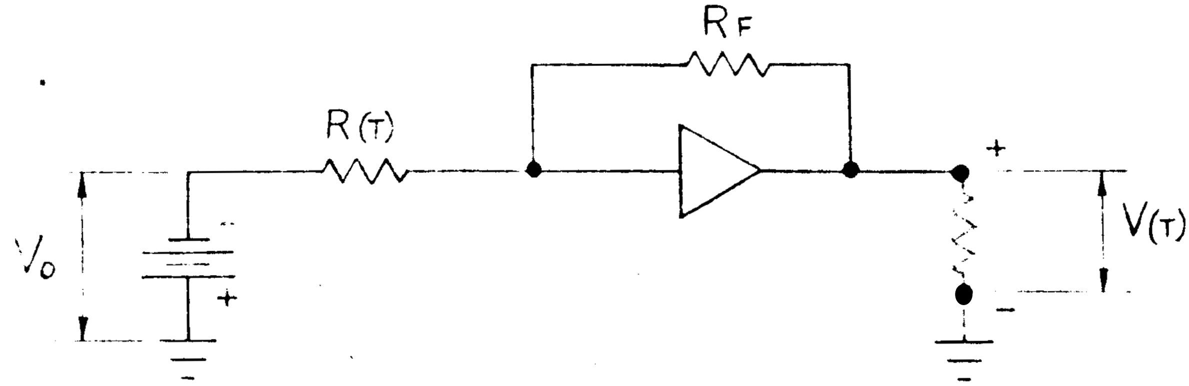

FIGURE 1

An operational amplifier receives a constant input voltage V_o. The output voltage $V_{(T)}$ depends on its gain which varies with $R_{(T)}$ and therefore with temperature.

$$V_{(T)} = -\frac{R_F}{R_{(T)}} V_o \quad (1) \tag{1}$$

The sensitivity in V/°C is obtained from (1) by differentiating:

$$\frac{dV_{(T)}}{dT} = \frac{R_F}{R_{(T)}} \cdot \frac{\frac{dR_{(T)}}{dT}}{R_{(T)}} V_o \quad (2) \tag{2}$$

$\frac{1}{R_{(T)}} \cdot \frac{dR_{(T)}}{dT}$ is the temperature coefficient of the thermistor $R_{(T)}$ and is fairly constant in the temperature interval of interest.

$R_{(T)}$, the thermistor resistance, appears in the denominator of (2). This means that $\frac{dV_{(T)}}{dT}$ will change inversely to $R_{(T)}$. $R_{(T)}$ decreases with temperature, causing $\frac{dV_{(T)}}{dT}$ to increase, which was desired.

$R_{(T)}$ is an Isocurve thermistor of 100 K ohms at 25°C. This is the highest resistance available.

The dissipation constant of the selected thermistor is 1 mW/°C in still air. This is the worst condition with respect to self-heating.

When the maximum error produced by self-heating is limited to .11°C, then no more than .11 mW may be dissipated in the thermistor.

The maximum power is dissipated when the thermistor attains its lowest resistance, that is, at 50°C. It is

$$P_{(50°C)} = \frac{V^2}{R_{(50°C)}} \quad \& \quad V_o = \sqrt{P_{(50°C)} \times R_{(50°C)}}$$

By inserting:

$$V_o = \sqrt{.11\,mW \times 36\,k\Omega} = 2\,V$$

Therefore, the fixed voltage V_o must not exceed 2 V.

The feedback resistor R_F is chosen to obtain 5 V output voltage at 50°C. $R_F = V_{(50°C)} \times R_{(50°C)} \frac{1}{V_o} = 5 \times 36 \times 1/2 - 90$ K ohm.

From equation (2), we obtain the sensitivity at 0°C, 25°C, and 50°C by inserting the values of $R_{(T)}$ and $\frac{dR_{(T)}}{R_{(T)}\,dT}$ at these temperatures.

$$\frac{dV_{(0°C)}}{dT} = \frac{90}{420} \times 0.048 \times 2 = 20.6 \; mV/°C$$

$$\frac{dV_{(25°C)}}{dT} = \frac{90}{100} \times 0.0396 \times 2 = 71.3 \; mV/°C$$

$$\frac{dV_{(50°C)}}{dT} = \frac{90}{36} \times 0.0333 \times 2 = 167 \; mV/°C$$

From these sensitivities, the stability requirement for the amplifier is obtained. When allowing a maximim error of .25°C at 0°C and of .1°C from 25°C to 50°C, we then obtain

$$\Delta V_{(0°C)} = 5 \text{ mV}$$

$$\Delta V_{(25°C)} = 7 \text{ mV}$$

$$\Delta V_{(50°C)} = 16.7 \text{ mV}$$

The test results compare favorably with these values.

3.2.2 The Amplifiers

Three possibilities for amplifier design exist:

1. a DC amplifier
2. a chopper amplifier
3. an AC amplifier

DC and chopper amplifier could use DC as input while an AC amplifier would require an AC input signal and therefore AC excitation for the thermistor network. The excitation voltage for the thermistor network must be kept constant, be it DC or AC. It is far more difficult to produce a constant AC voltage than a constant DC voltage. This rules out the AC amplifier.

The chopper amplifier employs a chopper transistor and a demodulator circuit. This leads to a large number of components some of which are very bulky (coupling capacitors).

The DC amplifier is the most compact of the three but demands expensive transistors in order to meet the zero stability requirement.

Considering the already critical size problem, preference was given to a DC amplifier approach.

Both DC amplifiers feature a differential input stage and a single ended output, and both are of the operational type. The first or buffer amplifier amplifies a fixed voltage obtained through voltage divider R7, R8. Its gain depends on the temperature because of the variation of R10. R9 is chosen in such a manner that at 50°C the output voltage is exactly 5 volts. At the lowest temperature interest (0°C) the output voltage will be approximately 300 millivolts. The input impedance of the circuit is very high. A bias current in the order of .2 A is sufficient.

The output impedance is very low and found to be below 10 ohms. This low output impedance makes the readout signal independent of variations in load.

The second or zero amplifier is almost idential to the first one. It differs in gain, and in that it receives a positive feedback signal from the switching circuit. This positive feedback which becomes effective whenever the switching action is initiated insures fast transients during switching. Zero amplifier and switch act together like a Schmitt trigger. This circuit, however, is superior to a conventional Schmitt trigger as far as stability and resolution is concerned.

4. TEST RESULTS

A large number of temperature test series were carried out on the amplifiers and the power supply. Corrective measures led to the final breadboard. The test results obtained from this circuit on two different days are shown in Tables 1 and 2. The measurements were taken at 0°C, 25°C, 50°C and 75°C. $R_{(T)}$ was simulated by fixed resistors. The supply voltage V was varied and $R_{(T)}$ was simulated for 3 sensing temperatures. The readout voltage $V_{(T)}$ and the voltage regulator output V_{PS} were monitored. $\Delta V_{(T)}$ shows the change of $V_{(T)}$ in the entire ambient temperature range for 3 values of $R_{(T)}$. These results compare very favorably to the requirements for ΔV in Section 3.2.1.

Another set of measurements were taken during the test runs of Tables 1 and 2. These tests show the switch point stability. During these tests $R_{(T)}$ was simulated by a Helipot. "On" and "off" switching were observed and the corresponding values for $V_{(T)}$ recorded. Again, the results are very good and well within specifications.

5. REMAINING PROBLEMS

Versatility of application of the thermostat creates serious design problems. When used to sense the temperature at the bottom of a well drilled into a solid body, a certain resilience of the probe body would be required. On the other hand, exposure of the thermostat to shock and vibration would demand a very rigid design. These two requirements are contradictory, and so far could not be reconciled.

A number of difficulties arise from the necessity to seal the thermostat hermatically. Here we run into bonding problems, especially when good thermal isolation of the tip of the probe is required. Such a thermal insulation is necessary to keep the time constant of the thermistor at a minimum. Several design approaches have been tried, but all show that the solution would be an expensive one. The supplier for the thermistor sensors has predicted severe manufacturing problems that could not be handled within the scope of this contract. The simplest solution by far under these circumstances would be to use different probes for the different applications anticipated. According to our opinion this would lead to an optimum design for each individual requirement, whereas a "universal probe" must, by necessity, make compromises between the different applications.

5.1 Calibration

The calibration of the thermostat, especially of the switch point, requires very accurate temperature measurement. In addition, it is required to produce and maintain certain temperatures very accurately. During calibration, the probe will be immersed in a temperature bath. A survey has been made of temperature baths and control equipment which are commercially available. Good equipment of this type is used extensively in the chemical industry and research activities. However, most of it is not designed for accuracy and convenient temperature calibration. An additional disadvantage is a limitation when operating at low temperatures. Rosemount Engineering has developed for their own use a bath which appears to be the most suitable for our needs. Negotiations are presently being conducted to purchase it after a trial period.

6.0 FUTURE WORK

During the remaining period of this contract, the following work will be performed:

1. Packaging of the electronic circuit will be finalized.
2. The engineering model will be fabricated and tested.
3. A decision concerning the probe design will be made.
4. Five prototype units will be fabricated, calibrated and tested.

	$V_{(T)}$ at 0°C			$V_{(T)}$ at 25°C			$V_{(T)}$ at 50°C			$V_{(T)}$ at 75°C			ΔV
$R_{(T)}$ \ V	24V	28V	32V	24V	28V	32V	24V	28V	32V	24V	28V	32V	
33K	5.350	5350	5.351	5.355	5.355	5.355	5.355	5.355	5.355	5.352	5.352	5.352	5 m V
100K	1.802	1.802	1.802	1.803	1.803	1.803	1.802	1.802	1.802	1.801	1.801	1.801	2 m V
470K	.358	.358	.358	.357	.357	.357	.356	.356	.356	.356	.356	.356	2 m V
V_{PS}	21.35	21.40	21.47	21.00	21.00	21.00	20.69	20.75	20.76	20.40	20.40	20.40	
SWITCHING													
"ON"	3.112	3.113	3.114	3.115	3.115	3.115	3.113	3.113	3.114	3.112	3.112	3.112	3 m V
"OFF"	3.118	3.120	3.121	3.119	3.120	3.121	3.118	3.119	3.120	3.115	3.116	3.118	6 m V

TABLE 1.

	$V_{(T)}$ at 0°C			$V_{(T)}$ at 25°C			$V_{(T)}$ at 50°C			$V_{(T)}$ at 75°C			ΔV
$R_{(T)}$ \ V	24V	28V	32V	24V	28V	32V	24V	28V	32V	24V	28V	32V	
33K	5.354	5.354	5.354	5.356	5.356	5.356	5.355	5.355	5.355	5.351	5.351	5.351	5 m V
100K	1.800	1.800	1.800	1.800	1.800	1.800	1.800	1.800	1.800	1.799	1.799	1.798	2 m V
470K	.358	.358	.358	.357	.357	.357	.356	.356	.356	.356	.356	.356	2 m V
V_{PS}	21.35	21.45	21.45	21.05	21.05	21.08	20.73	20.73	20.73	20.35	20.35	20.35	
SWITCHING													
"ON"	3.117	3.116	3.117	3.117	3.117	3.117	3.116	3.117	3.118	3.116	3.115	3.116	3 m V
"OFF"	3.120	3.120	3.120	3.120	3.121	3.121	3.120	3.122	3.120	3.116	3.120	3.120	6 m V

TABLE 2.

MetroPhysics Inc. W.A. #645201

PRELIMINARY PARTS LIST

Solid State Thermostat
Contract NAS8-11625

Item	Ref. Design	Component	Description	Manufacturer	Type	Order #
1	Q1	Transistor	USN2N1613	Fairchild		USN2N1613
2	Q2,Q3,Q4,Q7, Q8,Q11,Q12,Q13	Transistor	USN2N718A	Fairchild		USN2N718A
3	Q5, Q6,Q9,Q10	Diff. Ampl. Stage	2N2920	Fairchild		2N2320
4	Q14	Transistor	USN2N1132	Fairchild		USN2N1132
5	Q15	Transistor	2N2034A	Silicon Trans.		2N2034A
6	CR1,CR2,CR3, CR5,CR6	Diode	USN1N483B	Fairchild		USN1N483B
7	CR4	Zener Ref. Diode	1N823	Motorola		1N823
8	T1	Transformer		UTC		DO-T37
9	C1, C3	Capacitor, Tantalum	1MF 10% 50V	Kemet	J	K1J50K
10	C2	Capacitor, Tantalum	22 MF 10% 35V	Kemet	J	K22J35K
11	C4	Capacitor, Tantalum	10 MF 10% 20V	Kemet	J	K10J20K
12	C5	Capacitor, Tantalum	6.8 MF 10% 6V	Kemet	J	K6R8J6K
13	R1	Resistor, Carbon	18K ohm 5% 1/4W	Ohmite	AB	
14	R4,R5,R23	Resistor, Carbon	51K ohm 5% 1/4W	Ohmite	AB	
15	R6	Resistor, Carbon	4.3K ohm 5% 1/2W	Ohmite	AB	
16	R11,R19	Resistor, Carbon	330K ohm 5% 1/4W	Ohmite	AB	
17	R15	Resistor, Carbon	18K ohm 5% 1/4W	Ohmite	AB	
18	R24, R28	Resistor, Carbon	2K ohm 5% 1/4W	Ohmite	AB	
19	R25	Resistor, Carbon	3K ohm 5% 1/2W	Ohmite	AB	
20	R26	Resistor, Carbon	33K ohm 5% 1/4W	Ohmite	AB	
21	R27	Resistor, Carbon	2.7 ohm 5% 1/4W	Ohmite	AB	
22	R2	Resistor,Metal Film	38.3 K ohm 1% 1/10W	IRC	RN55C	
23	R3	Resistor,Metal Film	14.7K ohm 1% 1/10W	IRC	RN55C	

PRELIMINARY PARTS LIST

Contract NAS8-11625

Item	Ref. Design	Component	Description	Manufacturer	Type	Order #
*24	R7	Resistor, Metal Film	2.37K ohm 1% 1/10W	IRC	RN55C	
25	R8	Resistor, Metal Film	4.75K ohm 1% 1/10W	IRC	RN55C	
26	R9	Resistor, Metal Film	90.9K ohm 1% 1/10W	IRC	RN55C	
27	R12, R20	Resistor, Metal Film	133K ohm, 1% 1/8W	IRC	RN60C	
28	R13, R21	Resistor, Metal Film	909K ohm, 1% 1/4W	IRC	RN65C	
29	R14, R22	Resistor, Metal Film	43.2K ohm 1% 1/10W	IRC	RN55C	
*30	R16	Resistor, Metal Film	17.8K ohm to 51.1K ohm 1/10 W	IRC	RN55C	
31	R17	Resistor, Metal Film	57.6K ohm, 1% 1/10W	IRC	RN55C	
32	R18	Resistor, Metal Film	1.5 M ohm 1% 1/2W	IRC	RN65C	
33	R10	Thermistor	100 K ohm	Fenwal	IsoCurve	MP/I Part # 100105
34	CR7	Rectifier				

* TO BE SELECTED

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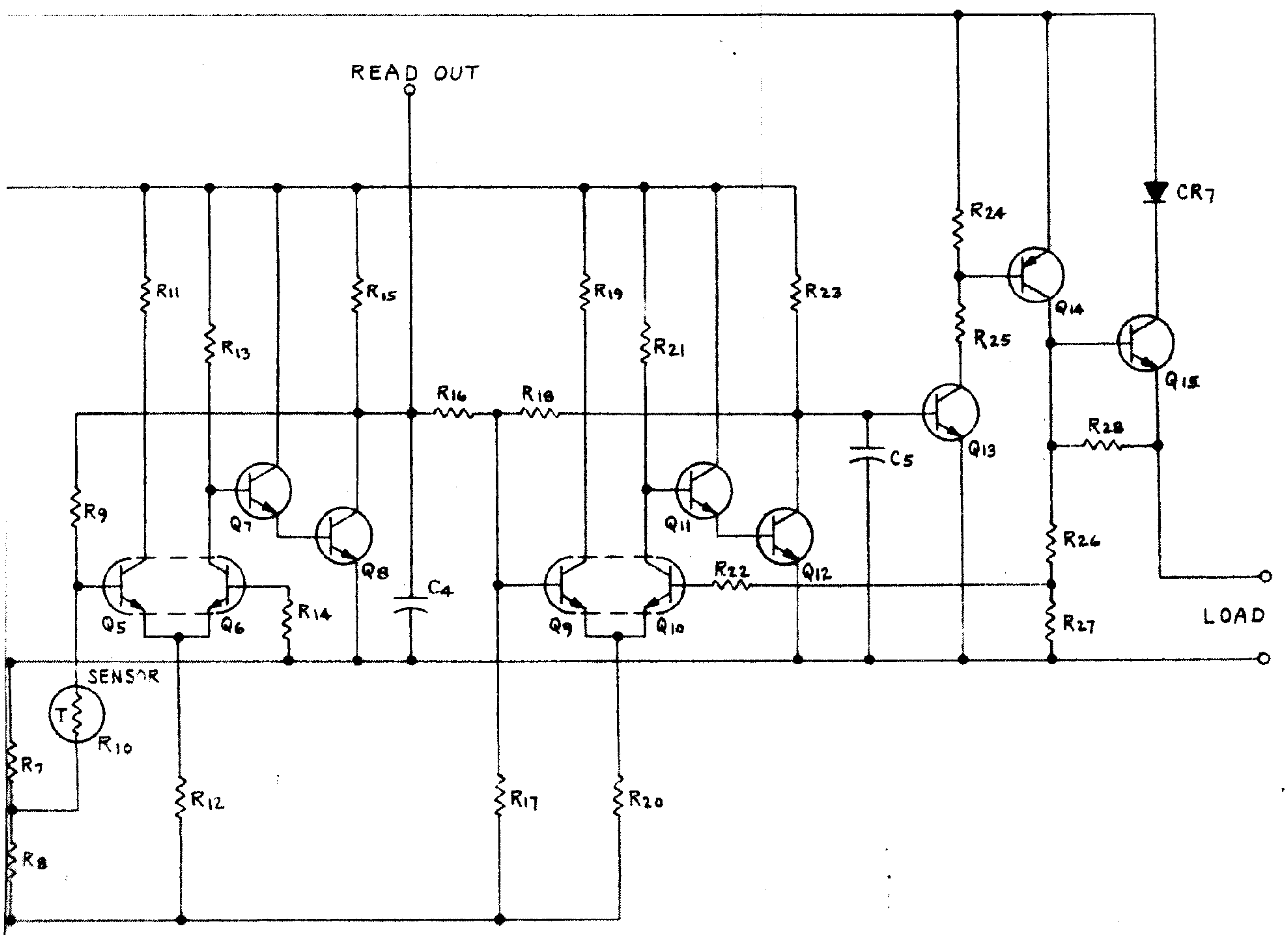

READ OUT
CR7
R11
R13
R15
R19
R21
R23
R24
R25
R16
R18
Q14
Q15
R28
C5
Q13
R9
Q7
Q8
C4
Q11
Q12
R26
R22
Q5
Q6
R14
Q9
Q10
R27
LOAD
SENSOR
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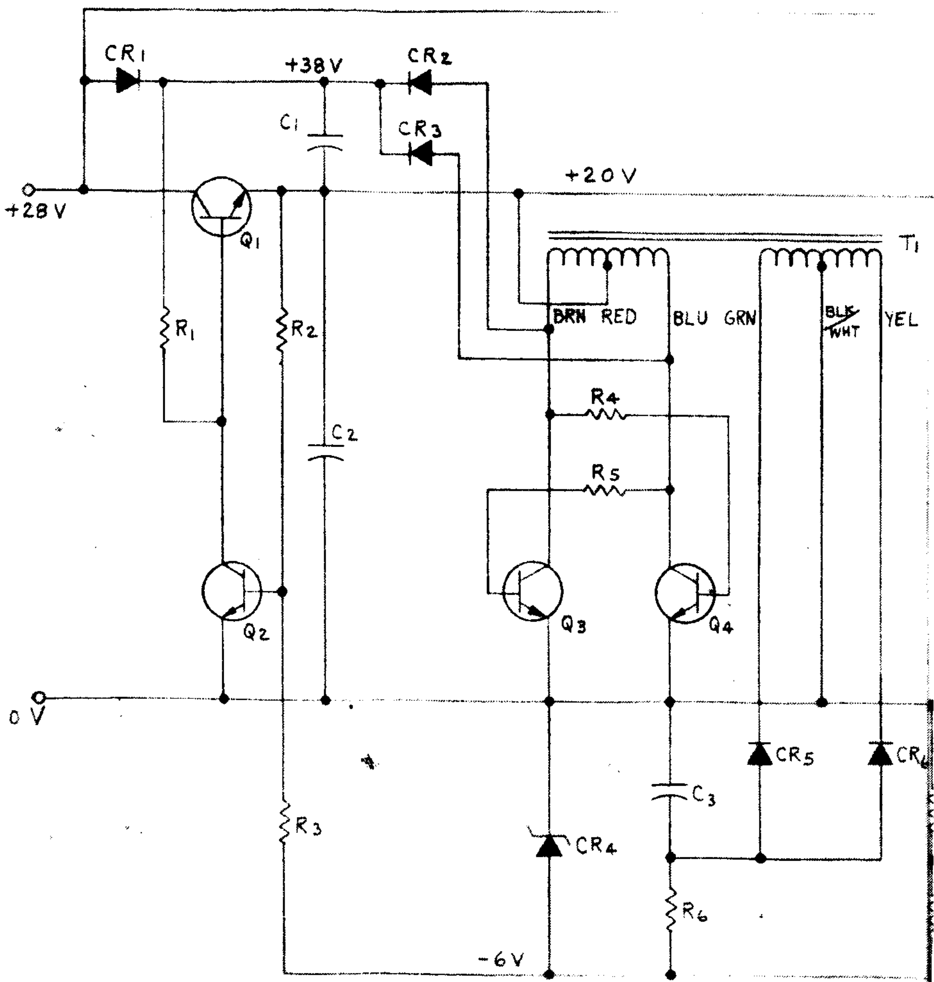
R10
R7
R8
R12
R17
R20



CR1
+38 V
CR2
C1
CR3
+20 V
+28 V
Q1
T1
BRN RED
BLU GRN
BLK/WHT
YEL
R1
R2
R4
C2
R5
Q2
Q3
Q4
0 V
CR5
CR6
C3
R3
CR4
R6
-6 V

METROPHYSICS INC., SANTA BARBARA, CALIF.

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DATE 8-17-64		REVISED

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